

On the influence of workpiece material on friction in microforming and lubricant effectiveness

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Abstract

The frictional behaviors between metal forming tool and three different metallic materials were evaluated using the modified T-Shape test. A mathematical function is proposed to describe the calibration curves for different friction coefficients. Round bars of copper, aluminum and silver of diameter 1 mm and length 5 mm were used as the workpieces to study the material influence on friction factor, m , during unlubricated microforming process through comparison between simulation and experimental results. Furthermore, various lubricants were used with the aluminum and copper to examine their performance in microforming. The results have shown that the workpiece materials not only determine the friction factor, m , during unlubricated microforming, but also influence the performance of lubricants. Lubricant can be completely ineffective and may not produce discernible friction reduction in microforming, unlike in

conventional metal forming. By considering the influence of contact pressure on lubricant effectiveness, a novel pressure dependent frictional model and a lubricant evaluation method are proposed.

Highlights

- Mathematical function for calibration curves in modified T-shape test is proposed.
- The effect of workpiece materials on the microforming friction coefficients is studied.
- The effect of lubricants on the microforming friction coefficients is extensively studied.
- A phenomenological friction model is proposed for liquid lubrication microforming.

Keywords

Friction coefficient, modified T-Shape test, exponential function for calibration curve, size effect, phenomenological friction model

1. Introduction

Development of miniaturization techniques has been a major contributor to new technologies in many segments of manufacturing industry. Industries such as IT, technology hardware and process automation for micro-processes have been boosted tremendously by the ever-developing techniques of miniaturization. As in the case of metallic micro-parts, their production at the present is dominated by micro-machining and MEMS-based processes. For general manufacturing, Altan et al. (2005) suggested that forming technology with its high productivity and low waste is generally preferred. Due to the demand to mass produce micro-parts, the boundary of metal forming processes has been steadily pushed to improve the general capability of forming at the smaller scale.

However, Geiger et al. (2001) revealed that the know-how in metal forming processes starts to break down when it is applied to microforming. Consequently, investigations on the mechanisms for the shift of material behaviors during miniaturization, or so-called the size effect, have become extensive in recent years. Among which, the shift of material mechanical properties and the change in frictional behaviors have been predominantly studied as summarized by Jeswiet et al. (2008). Microforming system is considered as a convolution of four individual aspects by Geiger et al. (2001): material, processes, tools and machine and the sources of size effects were categorized to physical (i.e. size effects influenced by the surface to volume size effect and relation of forces) and structural (i.e. size effects influenced by the grain distribution and surface roughness) by Vollertsen (2008).

Jeswiet et al. (2008) concluded that several past friction investigations in microforming have shown a significant size effect in lubricated contact, i.e. friction is increased with miniaturization. Geiger et al. (2001) presented a mechanical-rheological model based on the distribution of lubricant pockets on contacting surfaces. In such surfaces, the surface roughness naturally forms craters which subsequently become microscopic lubricant reservoirs. It was explained that the lubricant stored in craters closer to the edges of the surface is more likely to escape from the craters during contact making the lubrication ineffective in this region. Hence, as the components produced are miniaturized and the surface roughness remains relatively constant, the overall lubrication becomes less effective. This model has also been used in one of the investigations in Chan et al. (2011) to explain similar experimental findings of increased friction with miniaturization. Peng et al. (2010) used the lubricant pocket model further in a simulation to explain that friction behavior in microforming lies between conventional lubrication friction (low friction) and dry friction (high friction).

Prior microforming friction investigations used generic friction tests such as double cup extrusion test as reported by Geiger et al. (2001). Qin et al. (2008) outlined the importance of considering the tool-fabrication capabilities and tool cost when designing microforming process. Microforming designers need to consider the available technologies and processes which can be used to produce certain components for a new machine. It also includes the accuracy each technology or process can achieve and its respective cost. Thus in miniaturized tooling fabrication, intricate geometry is generally avoided to minimize the possibility of: a) imprecise fabrication, or b) expensive tool cost. Therefore, the use of conventional size friction test was deemed undesirable.

In addition, although it has been well understood that the magnitude of friction can be reflected by the forming load during metal forming process as investigated by Isogawa et al. (1992) through the use of spike test, the same may not apply in microforming due to the presence of size effects on material mechanical properties. Yun et al. (2010) presented an example of the size-dependent deviation of the mechanical properties in microforming and established the need to provide a novel constitutive material model to represent the workpiece in microforming process.

Various friction tests for metal forming processes such as the ring compression test (by Male and Cockroft (1964)), double cup extrusion (by Buschhausen et al. (1992)) and spike test (by Isogawa et al. (1992)) have been proposed and they were designed to identify the influence of contact properties, e.g. contacting materials, surface finish of the tooling and lubricant, to study frictional behavior during macro metal forming processes. As such, the typical characteristics of metal forming processes of high contact pressure and large amount of plastic deformation need

to be imitated in these friction tests. For adaptation to microforming friction investigation, there are added considerations of the tool-fabrication capabilities and tool cost, handling and characterization methodology.

Upon reviewing nine notable friction tests for metal forming, a modification to the T-Shape test was proposed by Taureza et al. (2012) as a friction test for microforming. The original T-Shape test was introduced by Zhang et al. (2009) to recreate the high contact pressure and plastic deformation which are characteristics of cold forging processes for macro size. The test produces co-existence of extrusion and upsetting metal flow similar to the process of micro-forging/extrusion process as performed by Ghassemali et al. (2013) which contributes to its friction-sensitive finished workpiece geometry. At macro size, the test has also been used to investigate high temperature forming behavior of magnesium alloys and the test showed repeatability of results by Fereshteh-Saniee et al. (2011). The modifications proposed by Taureza et al. (2012) include the higher length to diameter ratio and change in the characterization approach (both to ease material handling) as well as the change in die geometry for improved friction sensitivity. Figure 1 illustrate the construction of the original T-Shape test die with workpiece initial diameter of 7 mm and length of 7 mm alongside the modified geometry for initial diameter of 1 mm and length of 5 mm.

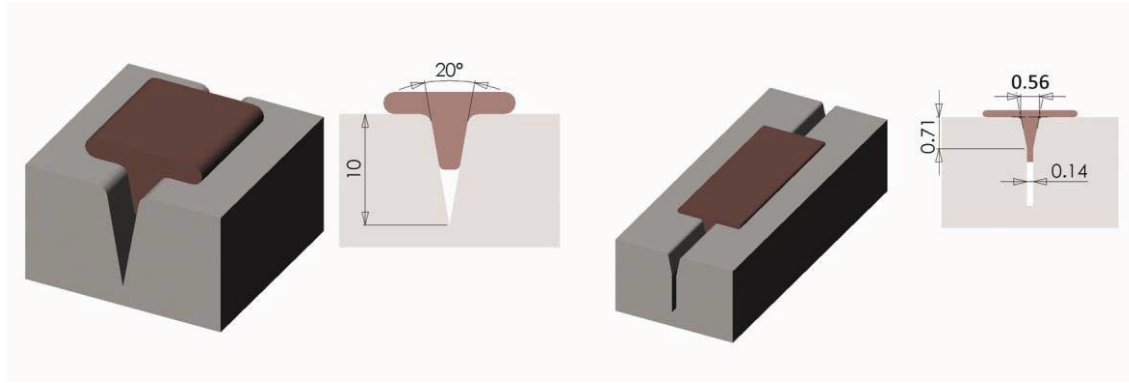


Figure 1: (Left) Original and (Right) modified T-Shape test

This paper presents the results on the influence of materials in contact to frictional behavior using the modified T-shape die setup. Three workpiece materials (copper, aluminum and silver) were selected as they are considered materials of interest in many industrial applications. All three materials possess face-centered cubic (FCC) crystal structures, hence such selection filters out the influence of crystal structures in the current investigation. The frictional behavior during the microforming friction test was evaluated through benchmarking with simulation results using friction factor, m .

2. Experimental setup

The Schmidt Servo Press 420 was used to perform the experiments. The punch-die assembly was fabricated from heat treated Hitachi SLD Magic steel with the surfaces polished to a surface roughness of R_a 0.08 – 0.12 μm . The modified T-Shape split dies used in the experiments are presented in Figure 2. Split dies were used in modified T-Shape test to allow post-test examination of tooling surface to inspect galling and defects on tooling surface.

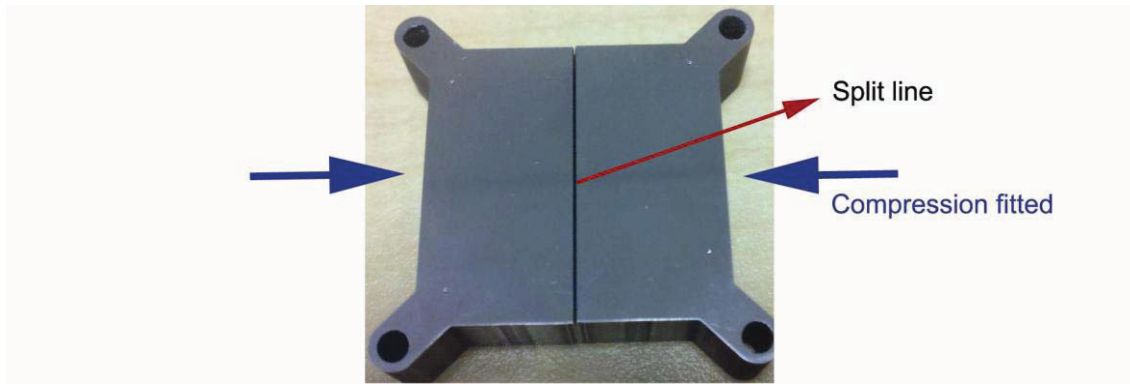


Figure 2: Modified T-Shape dies used in experiment

The workpiece materials chosen were 1 mm diameter aluminum wire with 99.5% purity and as drawn condition, 1 mm diameter silver wire with 99.99% purity and annealed condition as well as 1 mm diameter ETP copper wire. The miniature round bars for the experiment were prepared by cutting from a stock reel to 5 ± 0.5 mm length.

Alongside the experiments, **implicit** Finite Element (FE) simulation using Deform 3D and quarter-workpiece simulation domain (with approximately 30,000 elements, **Figure 3**) was conducted in order to produce friction calibration curves. Symmetry boundary conditions as illustrated in Figure 3 were prescribed on the symmetry planes as the four quarters of the workpiece are assumed to deform uniformly and the resource saved can be used to allow finer meshing to capture higher deformation details. During the simulation, the die is fixed as a rigid body and the also rigid punch is prescribed with a movement to -Y direction to compress the specimen and let the specimen develop the total height which depends highly on friction.

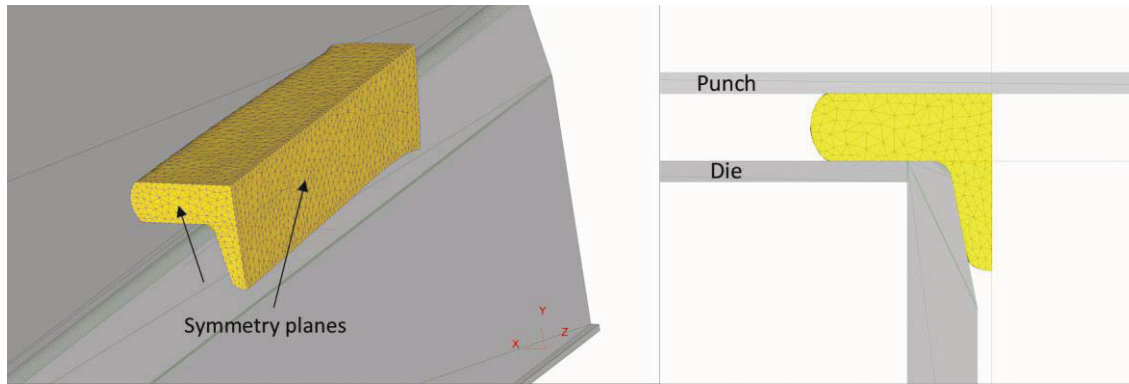


Figure 3: 3D quarter-workpiece T-Shape test simulation at 0.6 mm stroke

In metal forming processes, the interfacial friction between the tooling and the workpiece influences the material flow behavior. Similarly, in the modified T-Shape test, several characteristic dimensions of the workpiece after the test can be measured to indicate the magnitude of friction occurring at the interfaces during the test. The magnitude of friction is commonly quantified to a value of friction factor, m , or friction coefficient, μ . In order to approximate the magnitude of friction, experimental results are matched with known friction calibration curves. The simulation used constant friction factor, m , of 0.2, 0.4, 0.6 and 0.8 to create the calibration curves.

Therefore, friction calibration curves can be created from theoretical derivation (as shown by Danckert and Wanheim (1988)) or through simulation (as presented by Tan et al. (1998)). Due to the ease of FE simulation in recent decades, the calibration curves in recent studies are mainly produced by simulation. The importance of having separate friction calibration curves for different materials has been observed by Danckert and Wanheim (1988). During the investigation, it was revealed that a set of friction calibration curves created for a particular material may not be accurate when used with different materials especially when the friction is

high or when there is significant difference in the materials' strain hardening behavior. Nevertheless, Taureza et al. (2012) presented a contradicting example and showed that the friction calibration curves in T-Shape test are non-sensitive to up to 10 percent flow stress deviation.

In the current study, the simulation results using workpiece material property of copper and aluminum showed no influence of mechanical property of material on the simulation results despite the difference in flow stress of copper which was approximately three times that of aluminum (Figure 4). Therefore, the test was considered to be non-sensitive to material properties and the same friction calibration curves are used throughout the study. Such material property non-sensitivity is a preferred virtue of a friction test, which is also demonstrated by the ring compression test commonly used in the industry practice.

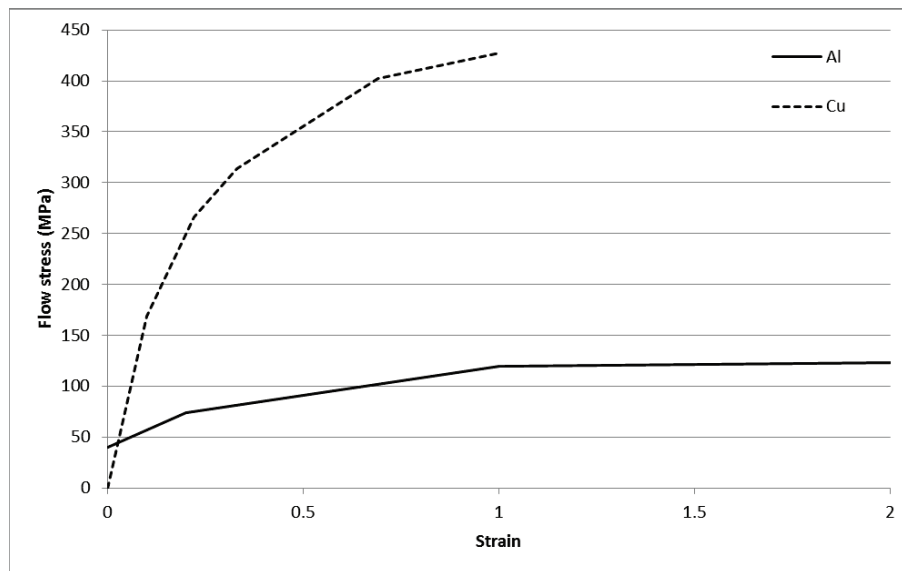


Figure 4: Flow stress of aluminum and copper in simulation

3. Results and Discussions

3.1 Evaluation of material influence to friction

In the modified T-Shape test, by setting variations in the punch stroke for each repetition, a set of formed specimens with different flange height between 0.05 to 0.30 mm was obtained. Each formed specimen is measured for its flange height (F) and total height (T , see Figure 5) to produce one data point to superimpose on the friction calibration curves. In Figure 6, the scatter of data points from the formed copper specimens suggests a friction factor (m) value between 0.4 and 0.6 as most suitable to represent the experiment.

As it is inconvenient to create calibration curves for all values of friction factors, the current calibration curves are limited to increment of 0.2 (i.e. 0.2, 0.4, 0.6 and 0.8). However, intermediate values of appropriate friction factors can be well estimated by adapting the available constant- m calibration curves to the regression function proposed here (Equations 1 and 2). The constants were determined from the available calibration curves as $C_1 = 0.6435$, $C_2 = -0.1872$ and $C_3 = -0.1973$. The chosen constants resulted in correlation coefficient R^2 of 0.9985, 0.9985, 0.9989 and 0.9977 for m value 0.2, 0.4, 0.6 and 0.8, respectively, which indicated very good agreement between the simulation result and the fitting from the regression equation. Overall, the known range of achievable friction factors in metal forming, i.e. 0 to 1.0 based on pioneering work by Hartley et al. (1979) and Bay (1987), is well represented and fitted by the function.

$$T = C_1 * F^{f(m)} \quad (1)$$

$$f(m) = C_2 + C_3 m \quad (2)$$

The significance of such function is that, it removes partially or to some extent fully, the need of plotting and interpolating the data point in the data calibration curve graph. By simply plugging in the measurement results F and T , the friction coefficient m can be provided by this mathematical function straightaway. Using this function, the average friction factor for the unlubricated experiments were easily calculated as $m = 0.473$ for copper as shown in Figure 6.

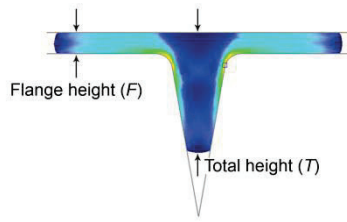


Figure 5: Measurements taken for modified T-Shape test

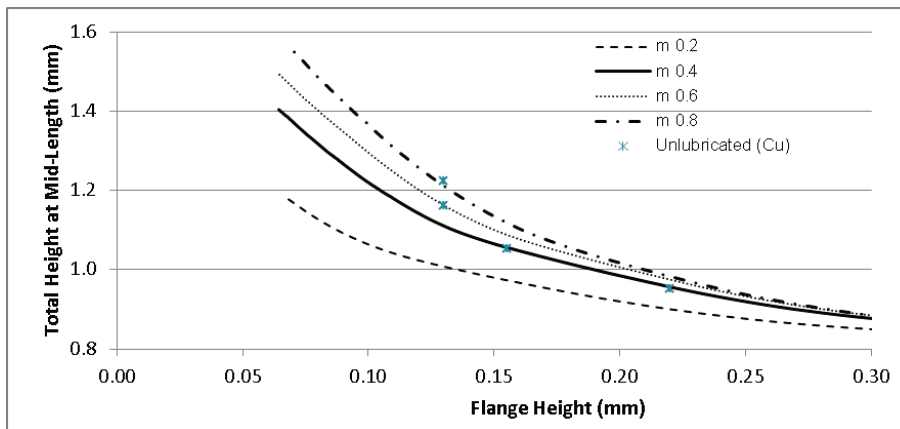


Figure 6: Unlubricated test results on copper

On the examination of aluminum specimens, a much higher average m value (exceeding 0.8) was observed from the experimental results as shown in Figure 7. Using Equations (1) and (2), the average friction factor for aluminum material was estimated as $m = 0.910$. During the

development of sheet galling test, Bernick et al. (1978) concluded that high static and dynamic friction stress is usually an indicator for galling. Although exceptions has been observed such as by Budinski (1981), galling generally increases friction as it **worsens** the quality of the tooling surface. The high friction in the Aluminum experiment was supported by the presence of galling marks on the die after the test (Figure 8).

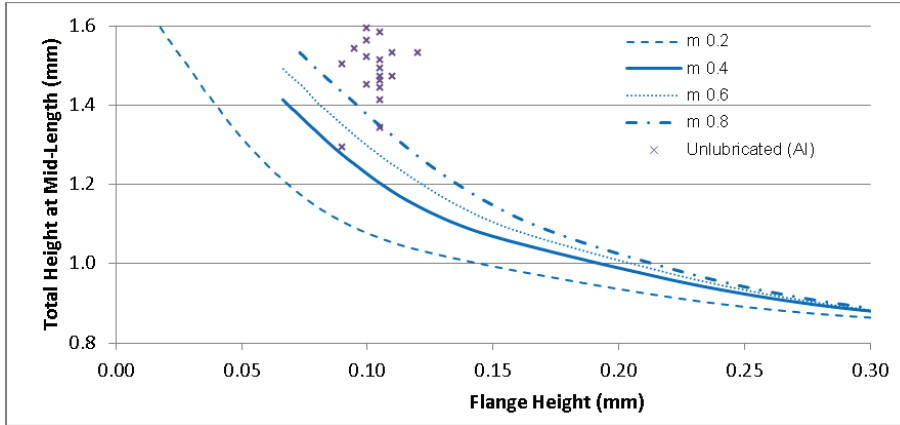


Figure 7: Unlubricated test results on Aluminum

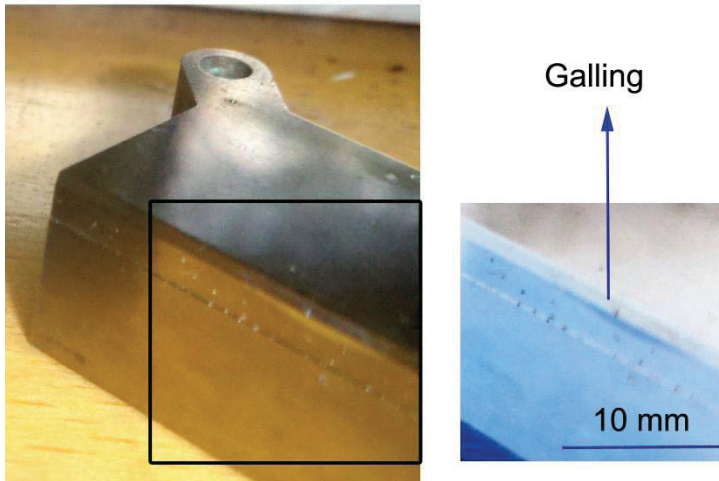


Figure 8: Positive and negative images of the die galling after aluminum experiment

The work of Schedin (1994) supports that the galling of aluminum compound worsens when aluminum oxide is present. Aluminum (III) oxide compound is known to form spontaneously at room temperature on surfaces of pure aluminum material and give the dull appearance of pure aluminum piece. Such galling was not observed from the copper and silver experiments.

The experiment using silver specimen showed intermediate m value of approximately 0.4 as presented in Figure 9. The calculations using Equations (1) and (2) estimated the average friction factor for silver as $m = 0.370$. The non-sensitivity of material mechanical properties to the test results means that the use of modified T-Shape test needs not be preceded by characterization of mechanical properties of the material for input in the simulation.

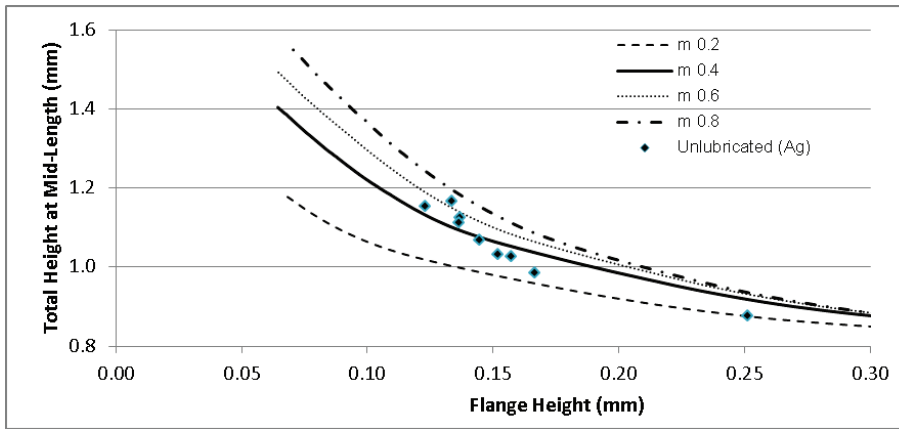


Figure 9: Unlubricated test results on Silver

Although the limit of this non-sensitivity of mechanical properties has yet to be explored, it is expected that the calibration curves for any material can be characterized by the constants C_1 , C_2 and C_3 (Equations (1) and (2)) which further reduces the need for extensive simulation for any future work involving the modified T-Shape test.

3.2 Evaluation of lubricant effectiveness

This multi-material examination validates the effectiveness of modified T-Shape test to distinguish different friction behaviors in unlubricated microforming setting. For the evaluation of lubricant effectiveness, various lubricants (both commercially available and prototypes) are tested and they are summarized in Table 1. The lubricants can generally be divided into three

groups based on the method of application: a) Aerosol spray (as supplied), b) Liquid supplied directly to surface and, c) Liquid supplied to surface followed by (non)-heated drying to expose the dried lubricant film. All the lubricants were designed for metallic contacts such as machining, sheet forming and forging. The lubricant evaluation was done only for copper and aluminum material as these materials provide high contrast in friction behaviors in the unlubricated studies, i.e. higher friction ($m = 0.910$) by aluminum and lower friction ($m = 0.473$) by copper.

The lubricants were supplied in abundance to ensure complete coating of the surfaces prior to deformation. The lubricated experiments were conducted in the same way as the unlubricated experiments in order to acquire specimens with various flange heights between 0.05 mm and 0.30 mm. The data points from the total height and flange height measurements were superimposed on the friction calibration curves as well as **used** in the mathematical function **(Equations (1) and (2))** to obtain their friction **factors**.

Table 1: Lubricants used in experiment

Name	Application	Composition or Intended use
<i>D1X (Prototype)</i>	<i>Dried Film</i>	<i>Water, wax, sodium stearate</i>
<i>D2X (Prototype)</i>	<i>Dried Film</i>	<i>Water, isophthalic acid, wax, graphite</i>
D3 (Commercial)	Dried Film	Sheet metal forming (warm)
L1 (Commercial)	Liquid	Machining
L2 (Commercial)	Liquid	Forging
<i>L3X (Prototype)</i>	<i>Liquid</i>	<i>Vegetable oil</i>
L4 (Commercial)	Liquid	Sheet metal forming
A1 (Commercial)	Aerosol Spray	Extreme temperature use
A2 (Commercial)	Aerosol Spray	High pressure use
A3 (Commercial)	Aerosol Spray	Heavy duty lubrication

3.2.1 Aerosol spray lubricants

Figure 10 presents the results from aluminum experiments using aerosol spray lubricants. Out of the three spray lubricants, A3 performed the best ($m = 0.375$) followed by A2 ($m = 0.546$) and A1 ($m = 0.694$). All m values were calculated using Equations (1) and (2).

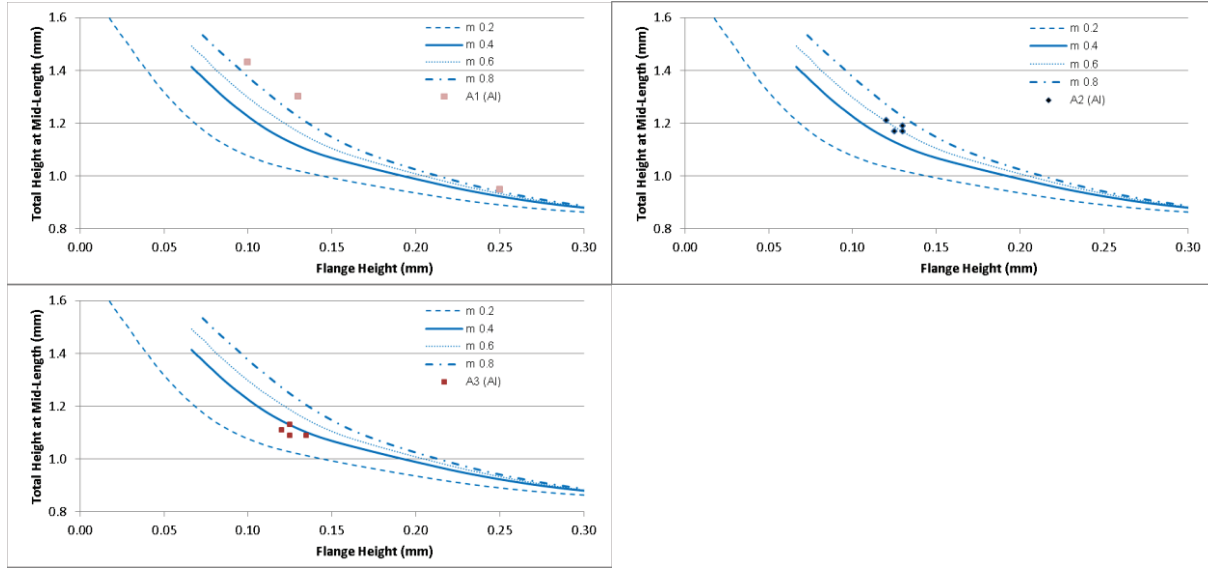


Figure 10: Aluminum experiment with aerosol spray lubricants

However, the resulting friction reduction was not the same when the workpiece material is replaced by copper, in which the lubrication performance of all lubricants was relatively similar ($m = 0.514 - 0.517$). Moreover, with copper material, the addition of aerosol spray to the setup did not result in significant friction reduction but a very small friction increment (Figure 11).

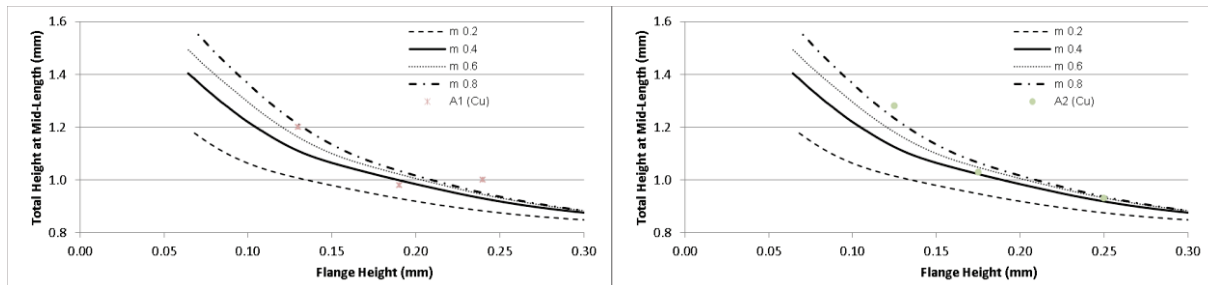


Figure 11: Copper experiment with aerosol spray lubricants

Therefore, in general it was concluded that for copper specimen, aerosol spray lubricants have no significant sign of effectiveness, i.e. the addition of lubricant for the test does not lower

the friction factor *in microforming*. Such reduced lubricant effectiveness has been documented in previous studies and explained by the lubricant pocket model, the results from the current study further indicated that the friction reducing performance of lubricants can even be negligible. This supports that the upper limit of friction in microforming, as proposed by Peng et al. (2010), is the dry/unlubricated friction. Aerosol spray lubricants are capable of reducing friction in the case of aluminum material to some extent in microforming. However, the lowest friction achievable with the current experiment is limited to $m = 0.4$ while in lubricated conventional metal forming process the m value can be reduced to below 0.2.

3.2.2 Liquid lubricants

When liquid lubricants were used in the experiment with Aluminum, the results, except with L2, showed that the behavior during the tests did not follow conventional m -based calibration curves (see Figure 12). Similar behavior was observed in the experiment with copper although the trend is not as significant as presented in Figure 13. More importantly, the experiment with copper did not produce significant friction reduction with all types of lubricants.¹

Throughout the range of flange height analyzed, all the liquid lubricants showed strong linear relationship between flange height and calculated friction factor for aluminum material (see Figure 14). In general, as the flange height decreases (and deformation progresses), the friction factor calculated is increasing linearly. In contrast, the friction reduction for copper material

¹ The lubricant L1 needs to be diluted in water prior to application. In this experiment, two grades of lubricant were formulated from L1 stock, a 10% solution and a 70% solution.

using liquid lubricants is marginal and there is no significant correlation between the flange height and calculated friction factor (Figure 15).

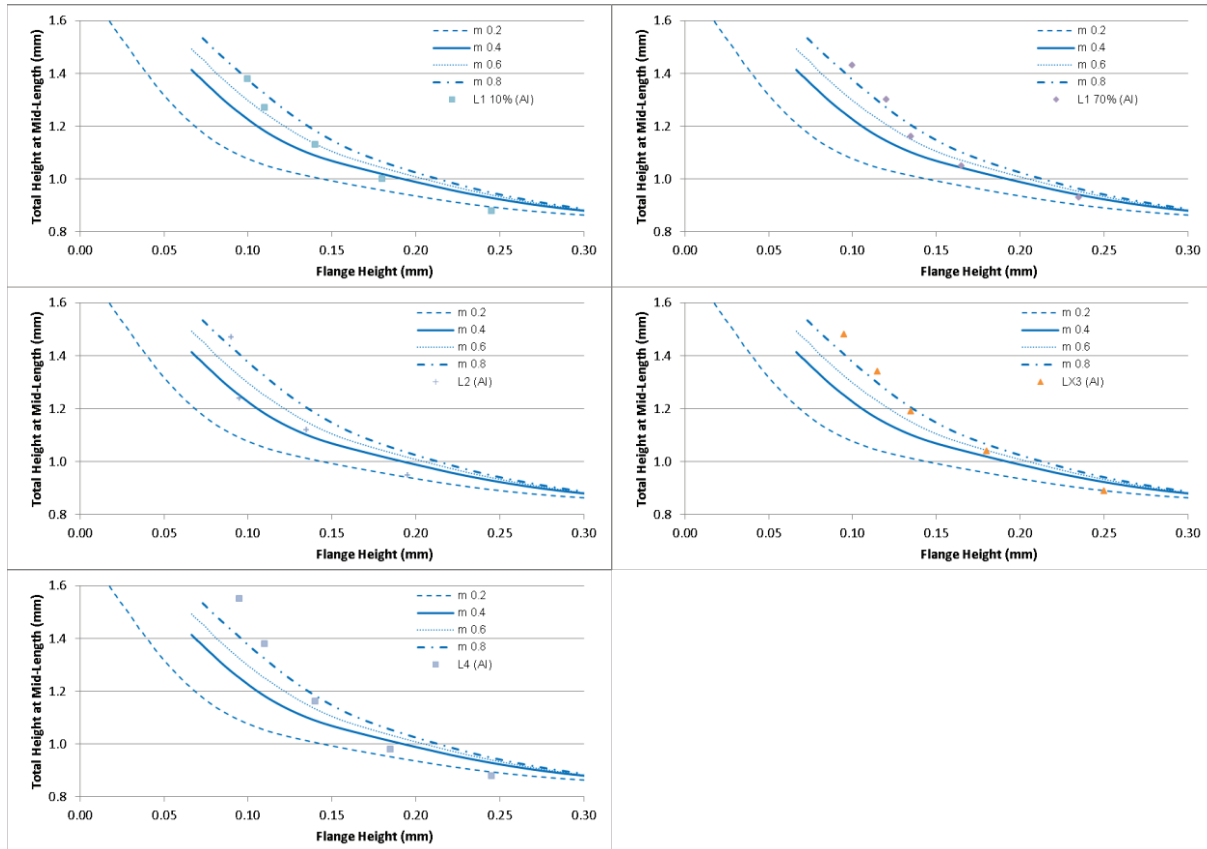


Figure 12: Aluminum experiment with liquid lubricants

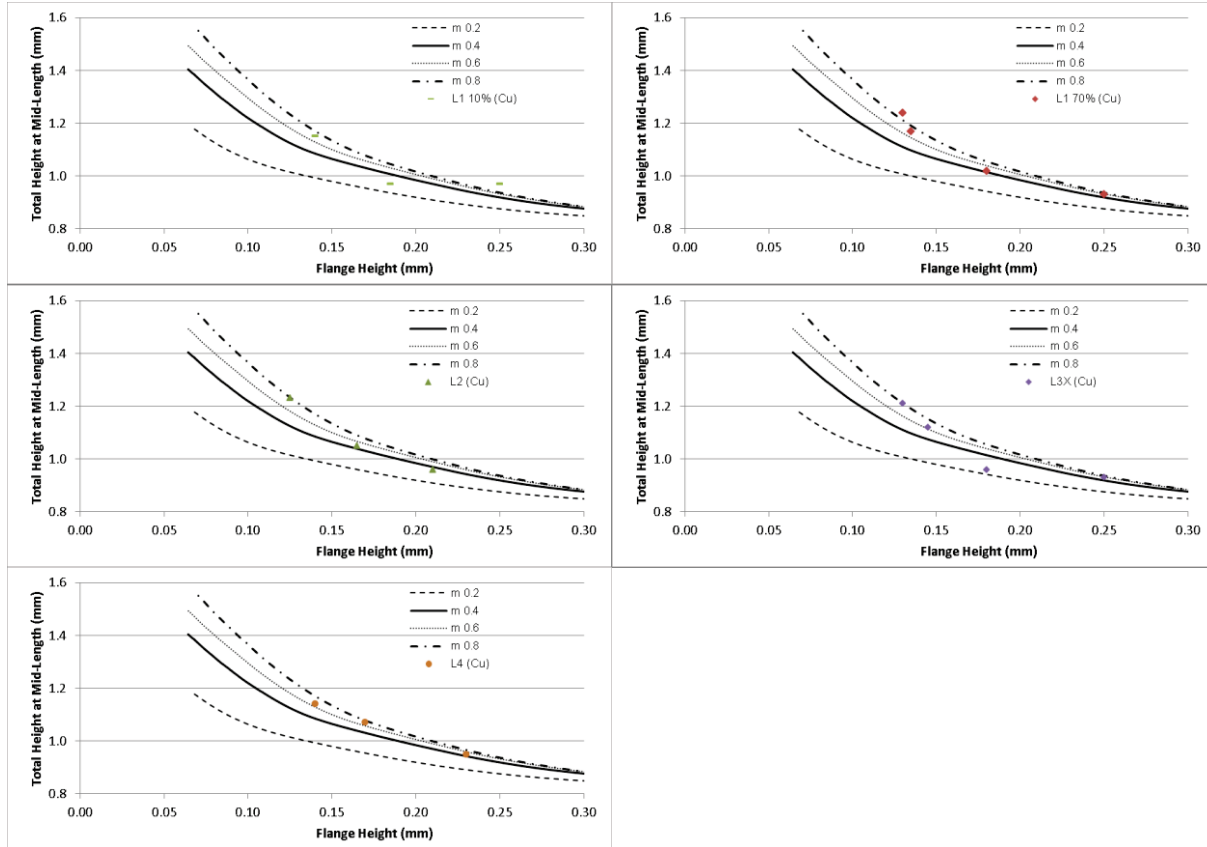


Figure 13: Copper experiment with liquid lubricants

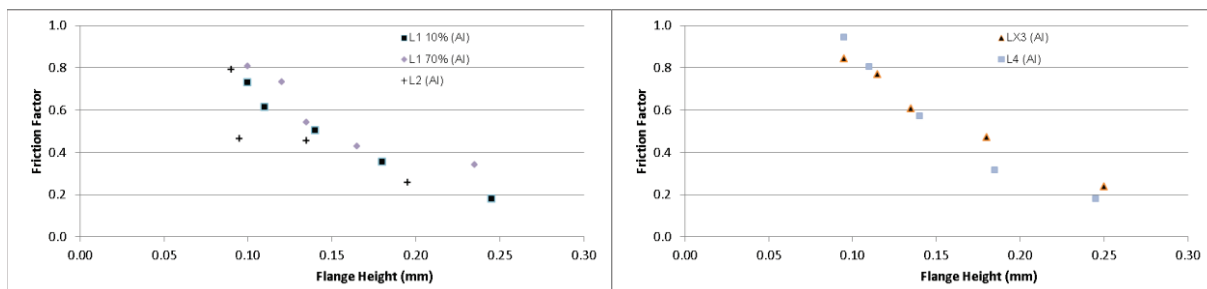


Figure 14: Increasing friction with deformation (Aluminum with liquid lubricants)

This behavior can be explained by considering the influence of contact pressure on the lubricant pocket model and therefore the lubricant effectiveness. The lubricant pocket model dictates that the lubricant reservoirs can be either effective reservoir (closed pocket) or

ineffective reservoir (open pocket) depending on the distance of it from the nearest open surface. The mechanism of evolution from effective to ineffective reservoir is attributed to lubricant leak as contact pressure builds up. Similarly, the amount of lubricant leak (and therefore lubricant effectiveness and friction) can therefore be proposed as a function of contact pressure (Figure 16). The pressure-dependent friction factor proposed here was inspired by the Avrami (1939) equation of phase change. In essence, the surface roughness forms effective lubricant reservoir at low contact pressure and this effectiveness decreases with increasing contact pressure.

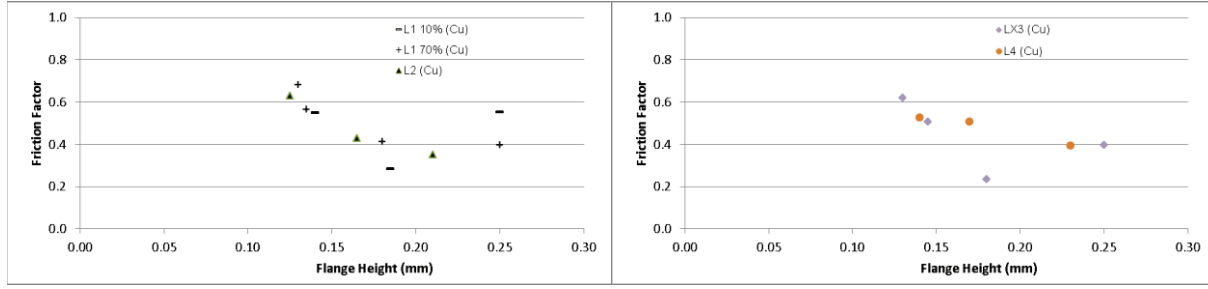


Figure 15: Constant friction with deformation (Copper with liquid lubricants)

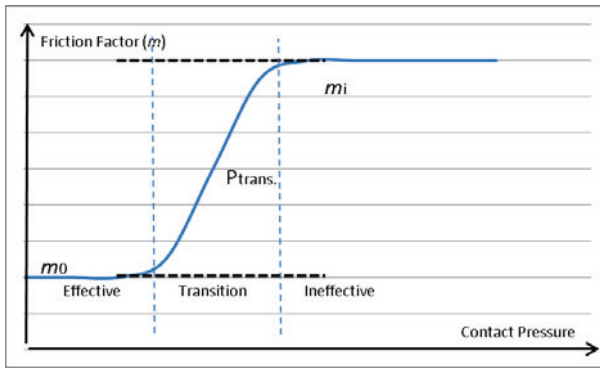


Figure 16: Frictional properties for microforming

The friction model is constructed using several parameters: m_0 the friction factor at effective lubrication region, m_1 the friction factor for ineffective lubrication and P_{trans} the transitional contact pressure. However, through sensitivity analysis using T-Shape geometry, P_{trans} was determined as the most critical parameter contributing to the test behavior. Therefore, the model was further simplified to only use the parameter P_{trans} . In the current study, simulation was further conducted to support the pressure-dependent friction factor model by relating to experimental results. In this investigation, the value of m_0 was set to 0.2 and m_1 to 1.0 (sticking friction). This pressure-dependent frictional behavior was therefore proposed as a method for more accurate representation of friction in microforming in simulation.

The determination of parameter P_{trans} for the various lubricants was presented only for aluminum experiment as the deviation from the constant- m calibration curves is more significant than for copper. Further simulation was conducted using Deform 3D to provide new friction calibration curves based on the pressure-dependent frictional properties. In Figure 12, better lubricants would produce data points at lower total height for the same flange height associated with lower friction. Similarly in Figure 17, better lubricants would produce the same behavior associated with higher P_{trans} , i.e. wider lubricant effectiveness window.

In Figure 17, the simulation results using pressure-dependent frictional properties are presented together with experimental results of aluminum with liquid lubricants. According to Figure 17, L1 70%, LX3 and L4 have similar P_{trans} of 150 – 200 MPa when tested with aluminum. The remaining two liquid lubricants showed marginally better friction reduction with higher P_{trans} . Critically, the liquid lubricants which do not follow constant- m friction calibration curves showed strong agreement to the proposed friction model which supports that lubrication in microforming can be described using pressure-dependent friction factor. In the case of L2, the lubricant is capable of producing constant friction factor throughout the range of contact pressure tested and therefore the experiment using L2 showed agreement with constant- m calibration curves.

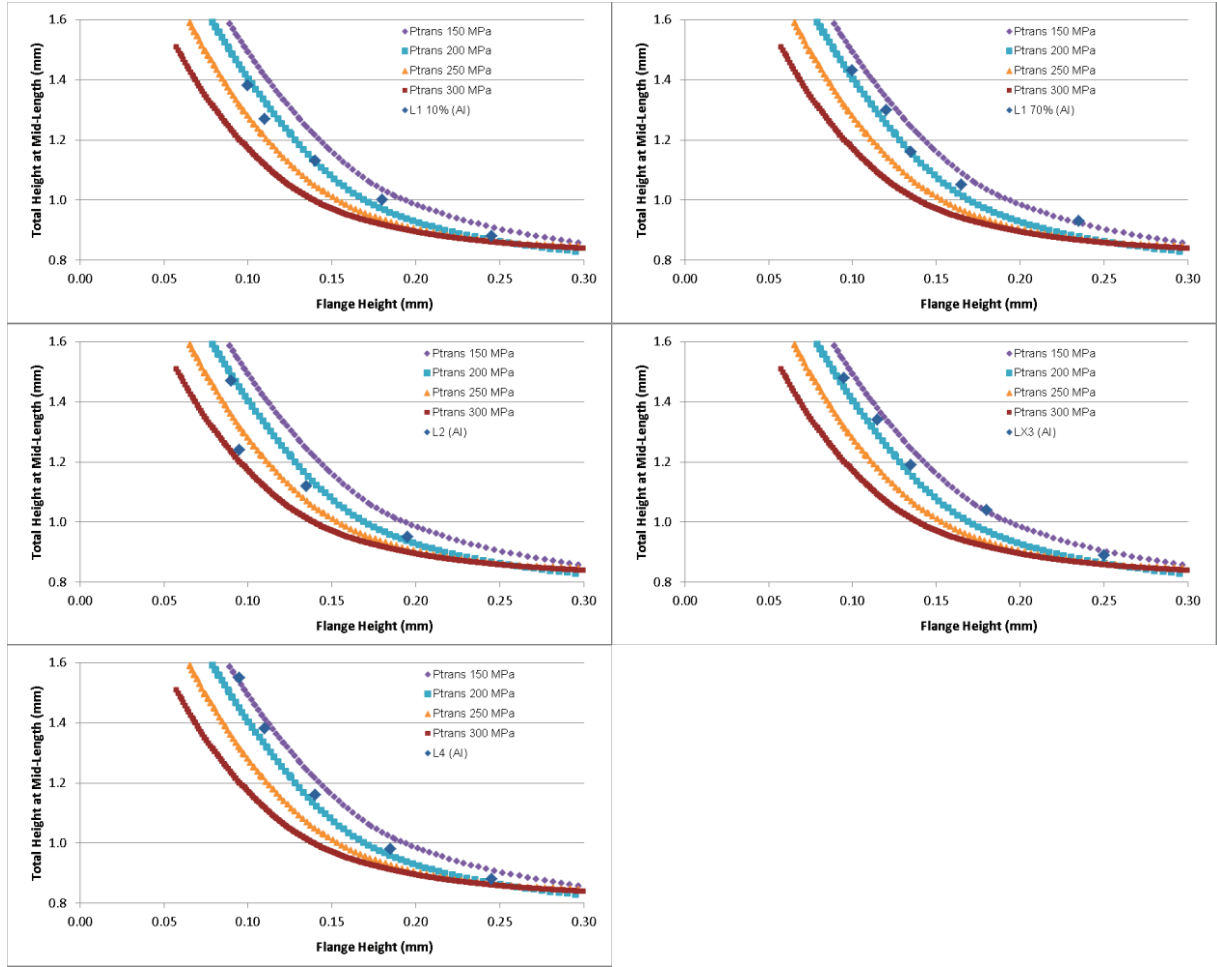


Figure 17: Liquid lubricants experiment with pressure-dependent friction calibration curves

3.2.3 Dried film lubricants

Deviation from the constant- m calibration curves was also observed when dried film lubricant was used as illustrated in Figure 18. As aerosol spray and liquid lubricants have no significant friction reduction on copper experiment, the dried film lubricants were tested only for aluminum. Figure 19 shows the experimental results of aluminum with dried film lubricants superimposed on the pressure-dependent friction calibration curves. Moreover, in contrast to

liquid lubricants, the dried film lubricants also do not follow the pressure dependent friction factor model as closely as liquid lubricants do.

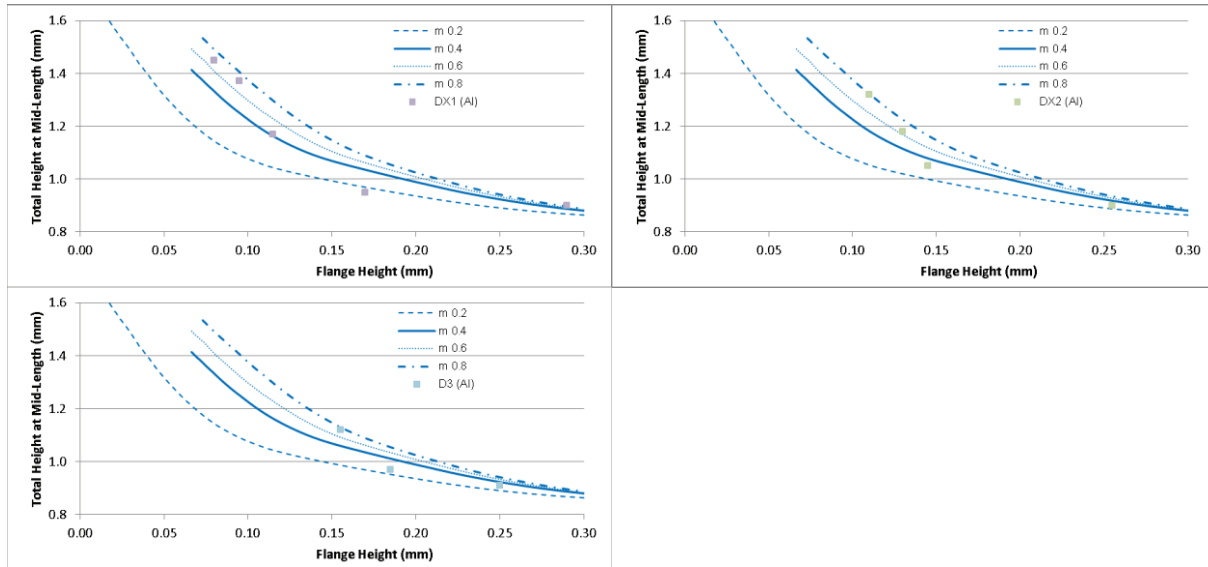


Figure 18: Aluminum experiment with dried film lubricants

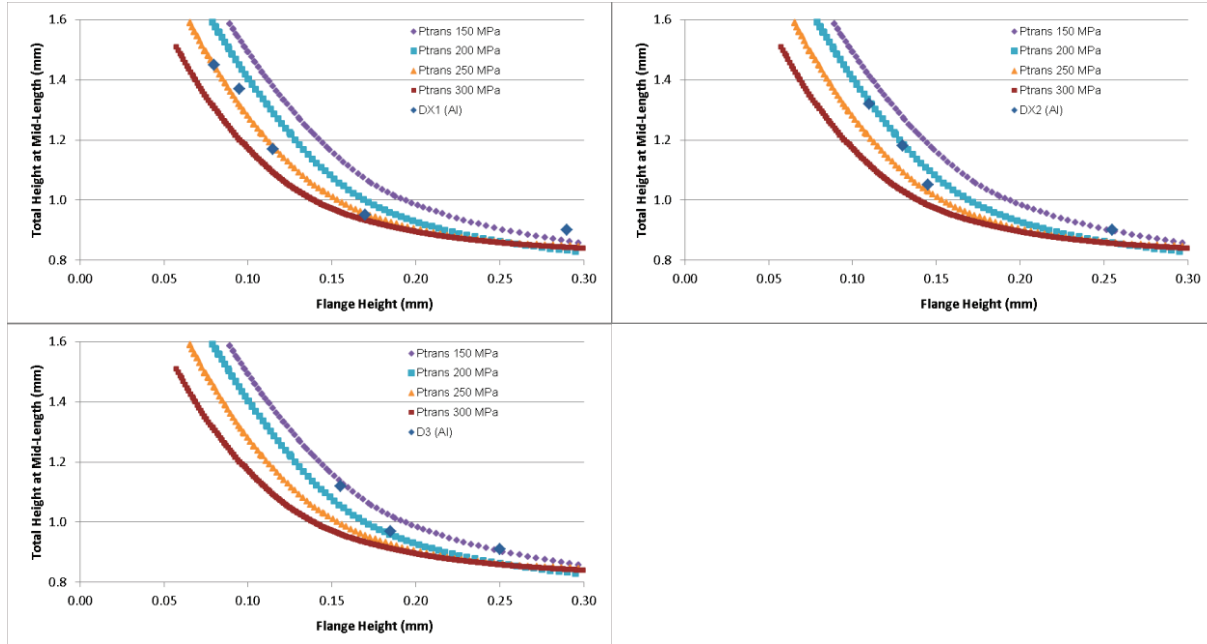


Figure 19: Dried film lubricants experiment with pressure-dependent friction calibration curves

The lubrication performance of the three groups of lubricants was evaluated using two workpiece materials, copper and aluminum. Generally, all the lubricants did not produce the desirable friction reduction associated with effective lubrication when copper material is used. However, when aluminum is used, the three groups of lubricant showed relatively good differentiation between each other. Spray lubricants generally showed accordance to constant- m calibration curves in the T-Shape test. The amount of friction reduction was also significant for A2 and A3. In the case of liquid lubricants, strong accordance to pressure dependent friction factor was observed and can be related to the lubricant pocket model.

Ultimately for dried film lubricants, the frictional behavior follows partly both sets of calibration curves. It is suggested that dried film lubricants carry both the traits of liquid lubricants because of their solvents and the traits of spray lubricants because of the nature of solid lubrication, i.e. friction is constant at low deformation (low contact pressure) and pressure-

dependent at high deformation (high contact pressure). Gallling was still observed for lubricated aluminum experiment although the amount of material transfer was relatively reduced.

Among spray lubricants, the lubricant A3 was considered best lubricant as it gives rise to the lowest friction factor. For liquid lubrication, the forging lubricant L2 was determined to be best as its performance is not pressure-dependent, i.e. lubricant leak associated with pressure build up is not significant. In comparison to machining or sheet metal forming processes, forging involves much higher contact pressure between tool and workpiece. The resilient performance of lubricant L2 from low to high pressure is consistent with the design as forging lubricant. Finally, the prototype lubricants DX1 and DX2 are incrementally better performers than lubricant D3.

4. Conclusion

The paper investigates the influence of materials on friction in microforming using modified T-shape die setup. A regression equation was proposed, to represent the calibration curves, to help eliminate uncertainty in determining friction factor from interpolation of limited calibration curves and improve the accuracy. The results have shown that in unlubricated experiment, the aluminum workpiece produced the highest friction factor, which may be explained by aluminum's likelihood to form oxide casing. Lubricated experimental results using aluminum also showed variations in lubricant behavior which depends on the constituents of the lubricant – solid, liquid or dried film. Specifically for liquid lubricant, a novel phenomenological friction model based on the mechanism of lubricant leak was proposed, so that the performance of liquid lubricants for microforming can be evaluated through their limit pressure of lubricant effectiveness (P_{trans}).

Acknowledgement

This work was undertaken as part of and was funded by the SIMTech Collaborative Research Project (CRP) U11-F- 015SU on Development and study of metal forming system(s) for micro components and features. The funding for this work was also supported by the Nanyang Technological University Research Student Scholarship.

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